Jet Propulsion Laboratory
California Institute of Technology

# A crash course in using tide gauges to study sea level

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This work has been conducted at the Jet Propulsion Laboratory, which is operated for NASA under contract with the California Institute of Technology.

# An outline of today's lecture

At the end of this lecture I hope you have answers to these questions

- Why do we have tide gauges and how do they work?
- Where are they located and how can I find the data?
- What signals can I expect in a tide-gauge record?
- How we can reconstruct regional and global sea-level changes from tide gauges

Feel free to ask questions!

# A quick history of tide-gauge observations, and where to get the data

# A quick history of tide-gauge observations

## Reading from a tide pole

Sources: Rijkswaterstaat Beeldbank and Phil Woodworth

## Tidal tables for sailors

JANUARY, 1781.

| D. H. M. | | D. H. M. | |
|---|---|---|---|
| First Qr. | 2 8 1 E. | Full Moon | 10 8 51M. |
| Laſt Qr. | 17 1 40M. | New Moon | 24 11 58M. |

| DAYS. | | Morn. | | Even. | | Heights | | Clock bef. Sun. |
|---|---|---|---|---|---|---|---|---|
| | | H. | M. | H. | M | F. | I. | M. |
| Monday | 1 | 3 | 3 | 3 | 24 | 13 | 0 | 4 |
| Tueſday | 2 | 3 | 47 | 4 | 11 | 12 | 4 | 5 |
| Wedneſday | 3 | 4 | 37 | 5 | 4 | 11 | 9 | |
| Thurſday | 4 | 5 | 34 | 6 | 6 | 11 | 8 | |
| Friday | 5 | 6 | 38 | 7 | 10 | 11 | 10 | 6 |
| Saturday | 6 | 7 | 44 | 8 | 13 | 12 | 6 | |
| SUNDAY | 7 | 8 | 41 | 9 | 7 | 13 | 5 | 7 |
| Monday | 8 | 9 | 31 | 9 | 55 | 14 | 5 | |
| Tueſday | 9 | 10 | 18 | 10 | 40 | 15 | 5 | 8 |
| Wedneſday | 10 | 11 | 2 | 11 | 24 | 16 | 5 | |
| Thurſday | 11 | 11 | 45 | ——— | | 17 | 4 | |
| Friday | 12 | 0 | 7 | 0 | 28 | 18 | 0 | 9 |
| Saturday | 13 | 0 | 50 | 1 | 13 | 18 | 3 | |

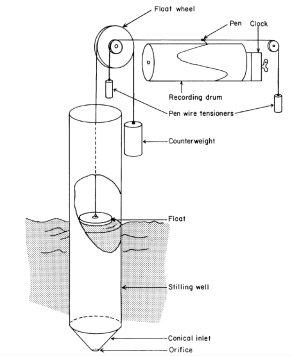
# From tidal measurements to long-term changes

Johannes Hudde, mayor of Amsterdam built benchmarks to create uniform height for flood defenses in 1675. One benchmark still exists today


Source: Phil Woodworth

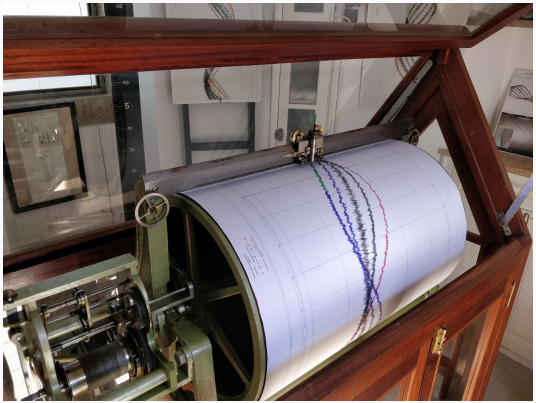
# From tidal measurements to long-term changes

## Automatic float tide gauges




Sources: Phil Woodworth, Wikipedia

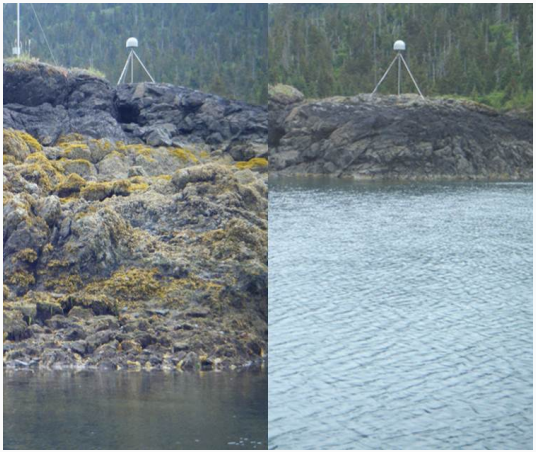
## From manual recordings to paper rolls



# Nowadays most tide gauges are equipped with more modern instruments

## Radar gauges

## GPS reflectometry



Sources: Phil Woodworth, Kristine Larson

# Where to find tide-gauge data?

There are multiple freely available databases with tide-gauge data.

Use the right database, depending on what you need:

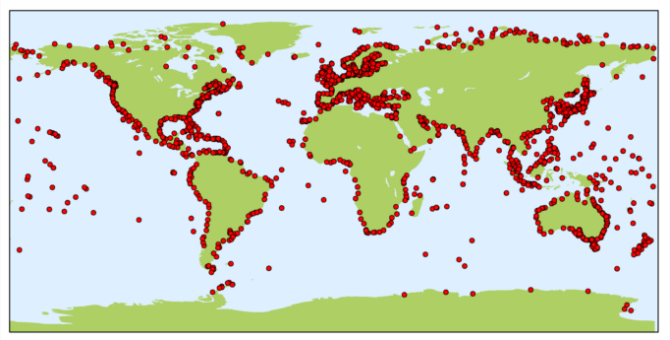
- High-frequency data (10-min, hourly or daily):
  - GESLA database (gesla.org)
  - University of Hawaii Sea Level Center (uhslc.soest.hawaii.edu)
  - Real-time data: VLIZ/IOC (www.ioc-sealevelmonitoring.org
- Long-term changes (monthly or annual data):
  - PSMSL: Permanent Service for Mean Sea Level (www.psmsl.org)
- But there is more! Local authorities, data rescue projects etc...

# Permanent Service for Mean Sea Level

PSMSL:

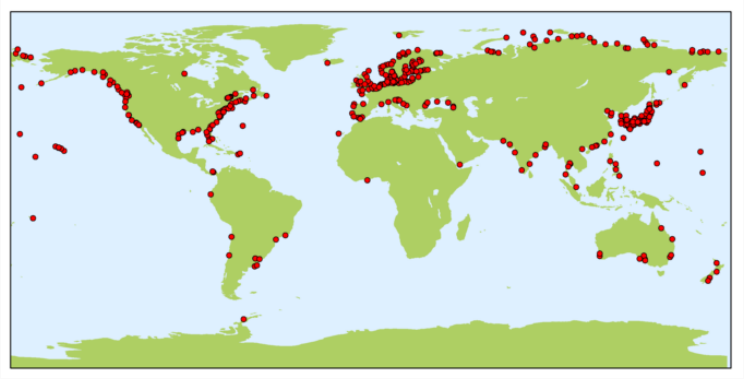
- collects
- analyses
- distributes

monthly and annual sea-level data



All stations for which PSMSL has data

# Long records



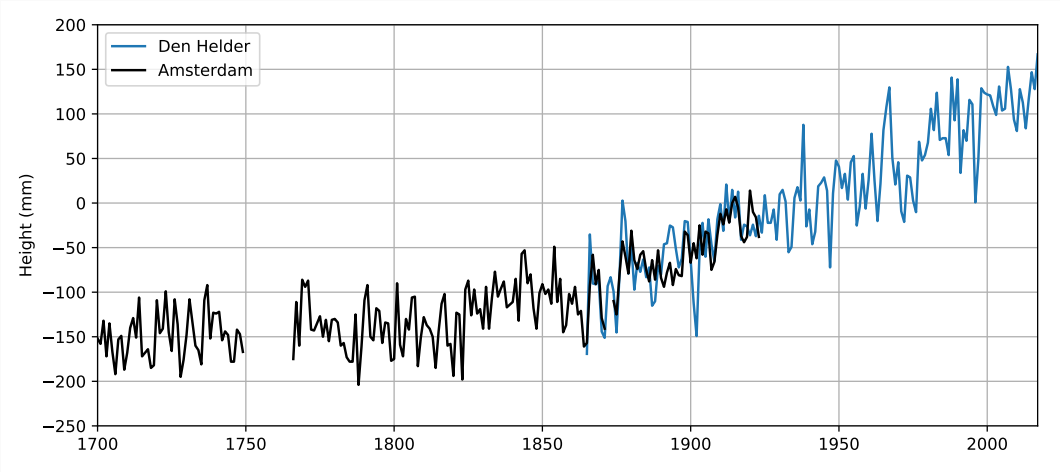
All stations with more than 40 years of data

Long records:

- Comparably few stations
- Not evenly distributed
- Southern hemisphere sparsely covered

# Long records: Amsterdam

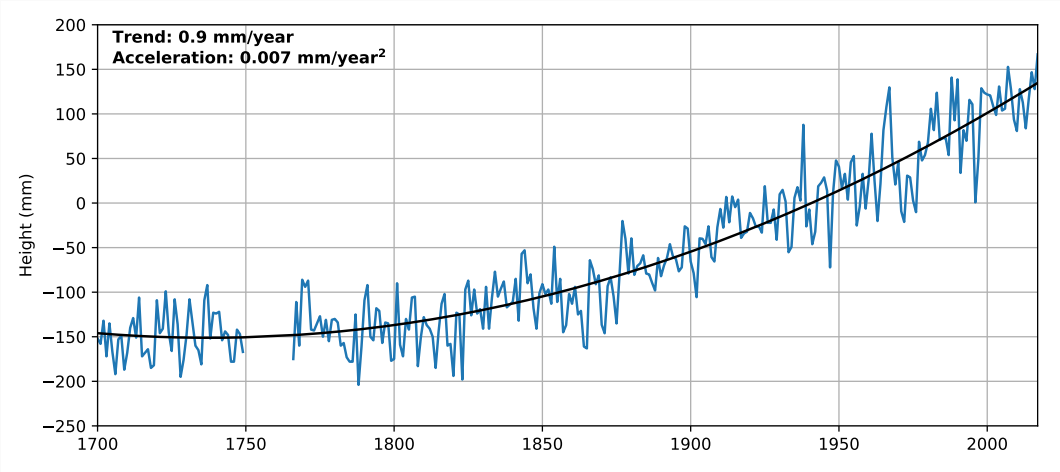
Oldest known tide-gauge record, thanks to Johannes Hudde




Source: PSMSL

# Long records: Amsterdam

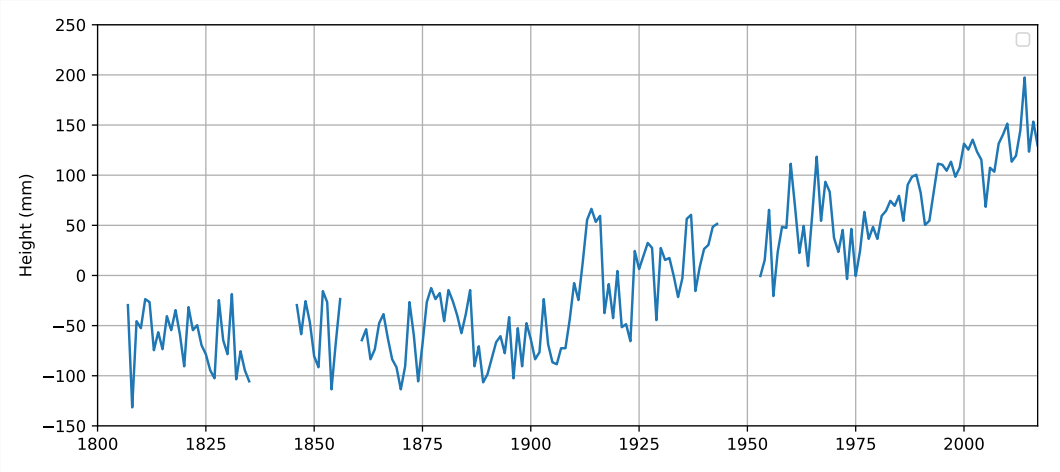
Record points at accelerating sea level:




Source: PSMSL

# Long records: Brest

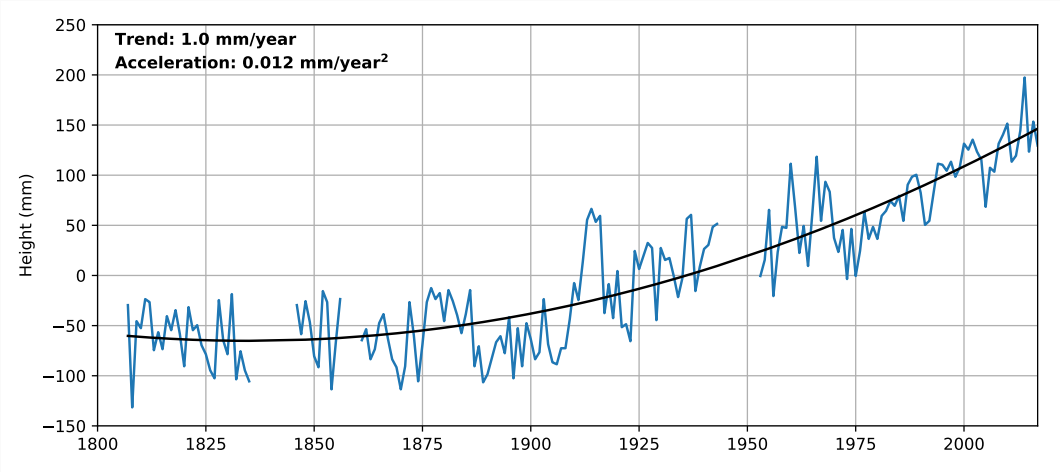
Oldest tide-gauge locations with ongoing measurements




Source: PSMSL

# Long records: Brest

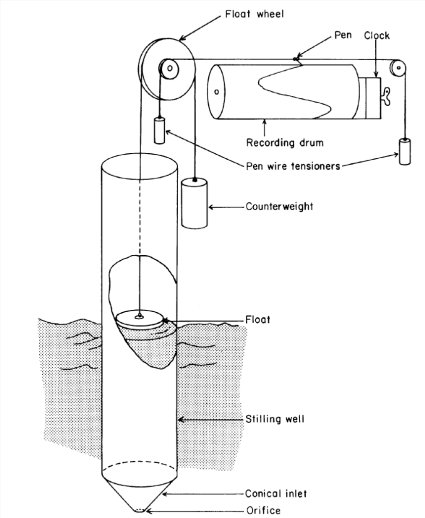
Also points at a sea-level acceleration




Source: PSMSL

# A few things to keep in mind when using tide-gauge data

# Tide gauges often use a stilling well, which removes high-frequency signals




Tide gauges often use a stilling well. This removes a lot of noise from the measurements, but a stilling well works as a low-pass filter:

- Effects of waves and tsunamis are not recorded or distorted
- A stilling well does retain tides and surges
- Tide gauges are often in harbours and thus do not measure in the ocean directly

Make sure that the tide gauge records the signal you're looking for!

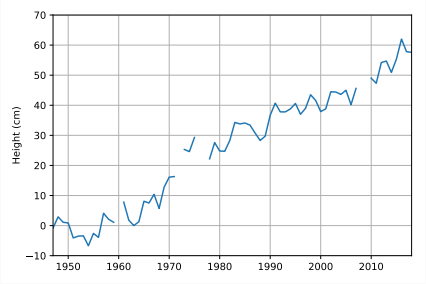
# Tide gauges are on land, and thus move with the land

Tide gauges measure sea level relative to land. If land moves, it will be recorded as a sea-level change!

- Subsidence and earthquakes can dominate the observed signal
- Local effects from ice sheets and GIA (other lectures!)

Be sure that you isolate the process you're looking for!

Subsidence in Grand Isle, near New Orleans




Source: PSMSL

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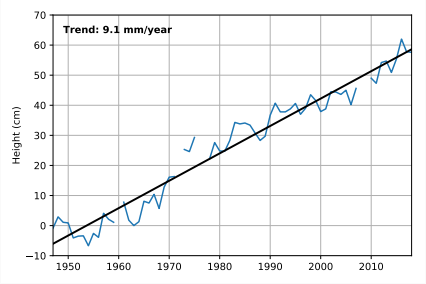
Example: subsidence in Grand Isle, near New Orleans




Source: PSMSL

# Relative and geocentric sea level

We call sea-level changes relative to the land *Relative Sea Level* (RSL) changes

- Tide gauges tell you RSL changes

We call sea-level changes relative to the center of the Earth *Geocentric Sea Level* (GSL) changes

- Satellite altimeters tell you GSL changes

The difference between both is *Vertical Land Motion* (VLM)

$$GSL = RSL + VLM$$

IJmuiden TG with GPS to measure VLM

# Datum control

Tide gauges measure sea level relative to some benchmark.

- We call this benchmark the 'datum'.
- Some countries use their national datum system to refer sea level (NAP in the Netherlands, Normal Null in Germany, and many others)
- Often, datum differs from tide gauge to tide gauge
- Relevant for mean sea level, but less so for sea-level changes.

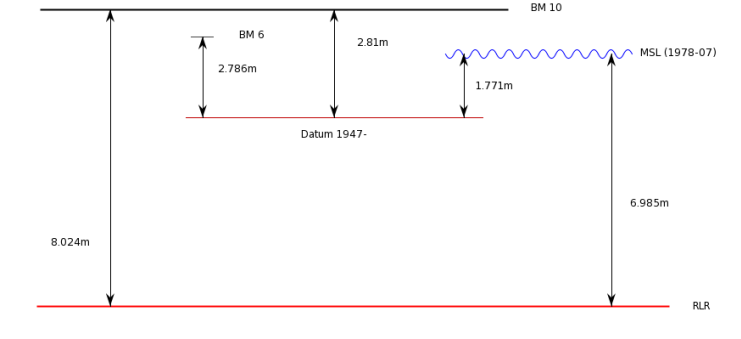
**Be aware of the datum when comparing two records!**


Sources: NOAA, Rijkswaterstaat

# Datum control

One important task of PSMSL: datum control.

- Level subsiding and replaced tide gauges to stable benchmarks
- RLR diagrams
- Ensures that you're looking at sea-level change



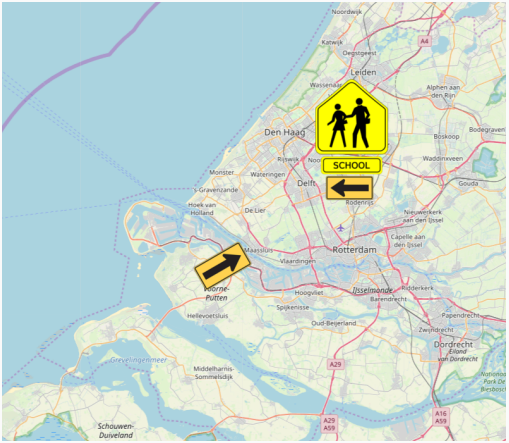

**Bottom line: always use Revised Local Reference (RLR) data and read the documentation!**

# What signals can I expect in a tide-gauge record?

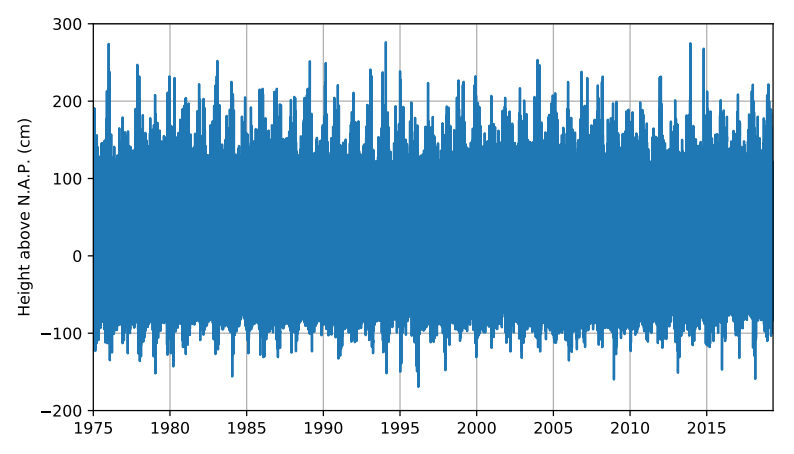
# Let’s have a look at some real data!

The tide gauge in Maassluis is the nearest tide gauge station from this lecture hall that has a long and high-frequency record available.

- Hourly data since 1970
- Monthly and annual sea-level data from 1848



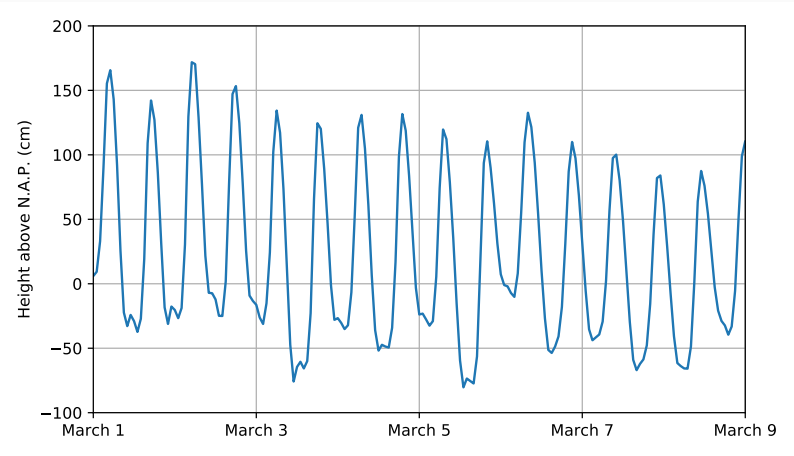
# High-frequency observations




Data source: Rijkswaterstaat

# Let’s zoom in a little bit (Spring 2017)

Tides form the largest signal.



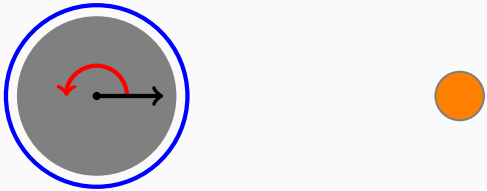

Data source: Rijkswaterstaat

Tidal equilibrium

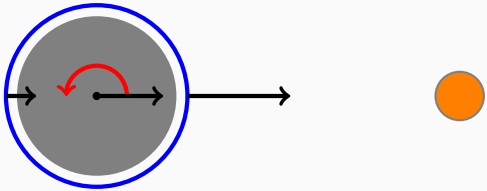
# A crash course in tides: the tidal potential

Tidal equilibrium

- Moon attracts water



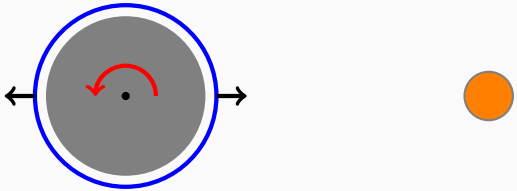
# A crash course in tides: the tidal potential



Tidal equilibrium

- Moon attracts water
- Ocean near moon more attracted than far side

# A crash course in tides: the tidal potential



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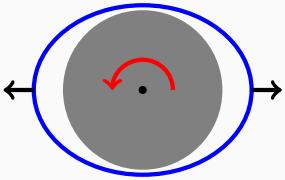

Tidal equilibrium

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- Two tidal bulges: semi-diurnal tide

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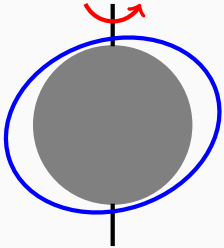


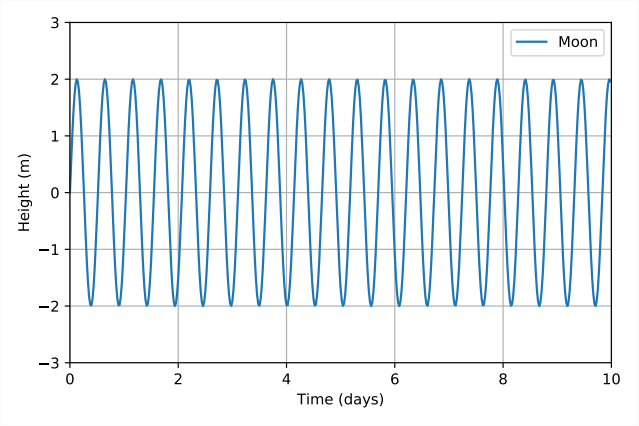
Tidal equilibrium

- Moon attracts water
- Ocean near moon more attracted than far side
- Potential when we remove the body force
- Two tidal bulges: semi-diurnal tide
- Earth rotation axis is tilted, creating one larger and one smaller tide every cycle

# Sun and moon

The sun also causes a (smaller) tidal signal

- Mean lunar day: 24.85 hours



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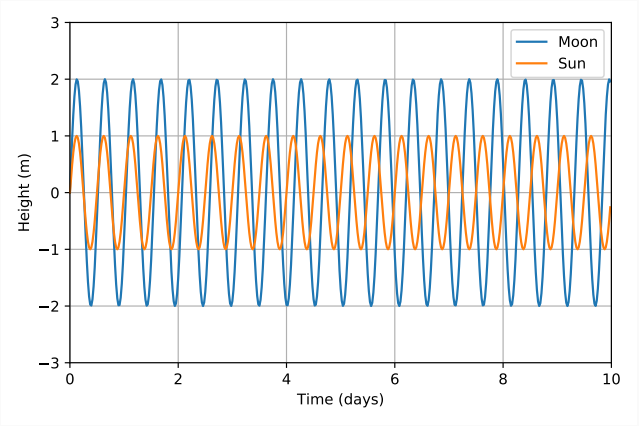
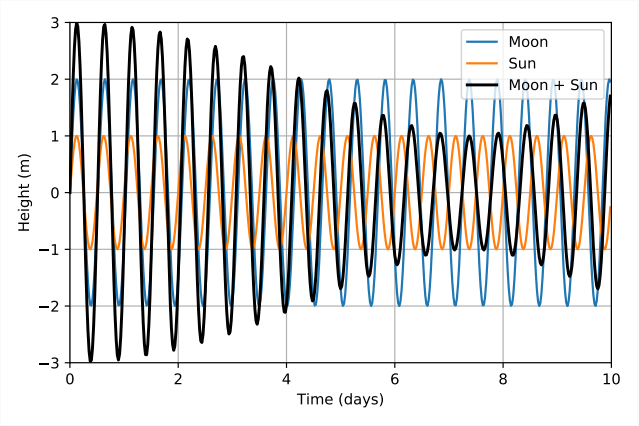
- Mean lunar day: 24.85 hours
- Mean solar day: 24 hours



# Sun and moon

The sun also causes a (smaller) tidal signal

- Mean lunar day: 24.85 hours
- Mean solar day: 24 hours
- Combination causes spring-neap cycle



# Equilibrium tides versus ocean tides

Ocean waves propagate too slow to adjust to tidal forcing:

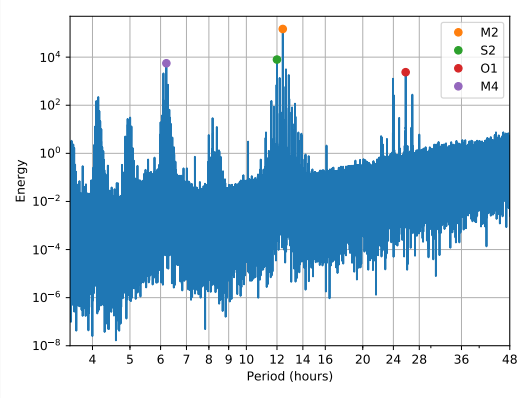
- Real ocean tides deviate from tidal equilibrium
- On shallow-shelves, tides become very complicated

Bay of Fundy (East Canada) has a tidal range of 15 meter

Source: Wikimedia Commons

# Tidal constituents

Periodogram of the Maassluis record

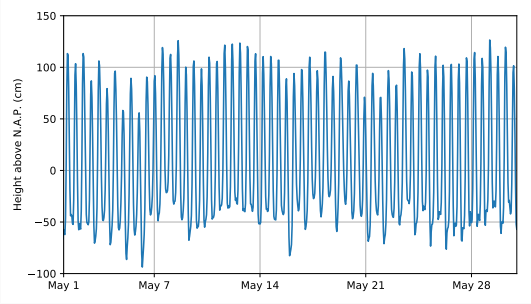



We can use a periodogram to estimate the tides:

- Peaks in the periodogram correspond to periodic signals. Higher peak: stronger cycle.
- We call these frequency peaks 'tidal constituents'
- We can spot the cycles due to the moon (M2) and the sun (S2)
- Tilt of the Earth axis: O1
- Many more tidal constituents!

# Estimating and predicting tides using least squares

Maassluis, May 2017




We can estimate the tidal signal using least squares:

- Estimate phase and amplitude of each constituent
- When we know them, we can also predict future tides
- Free Matlab/Python packages are available who do this for you! (UTide, t-tide, TASK)

# Estimating and predicting tides using least squares

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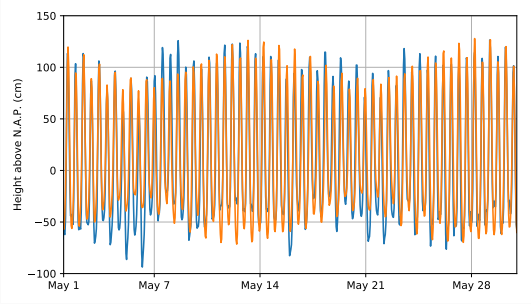


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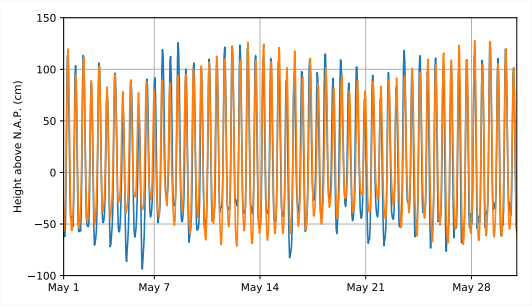
# Coffee time


SEA
LEVEL
bakery + coffee
CANNON BEACH
SEA
LEVEL
bakery + coffee

# Pressure, storms, and extremes

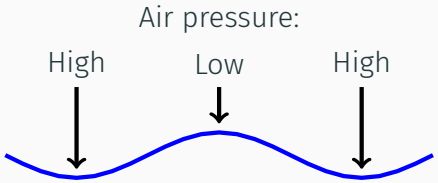
Maassluis, May 2017




Tides only partially explain the day-to-day variations. How about wind?

- Air pressure changes and wind affect sea level
- From the records, we can estimate expected storm-surge heights

# The inverted barometer effect




Air pressure pushes the ocean down.

High pressure: low sea level:

$$\Delta\eta = -\frac{1}{\rho g}\left(P_A - \overline{P_A}\right)$$

| | |
|---|---|
| $\Delta\eta$ | Sea-level anomaly (m) |
| $\rho$ | Water density (kg/m$^3$) |
| $g$ | Gravitational acceleration (9.81 m/s$^2$) |
| $P_A$ | Local pressure (Pa) |
| $\overline{P_A}$ | Mean pressure over ocean (Pa) |

Works well for open ocean, but less effective along coasts.

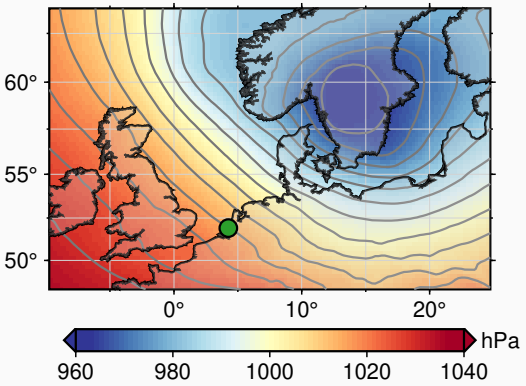
# The December 5, 2013 storm

Flooding in Dagebull, Germany

Water reaches homes in Boston, UK

Photo credits: PRI, Peter Macdiarmid, Carsten Rehder

# The December 5, 2013 storm

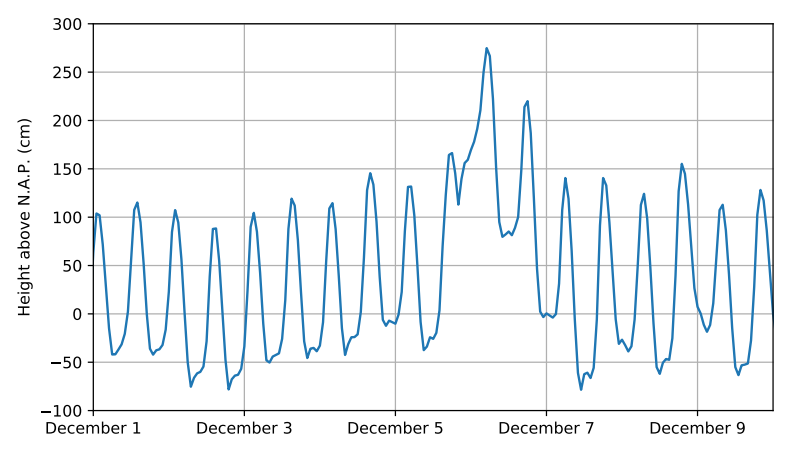



Source: ECMWF ERA5

The weather chart:

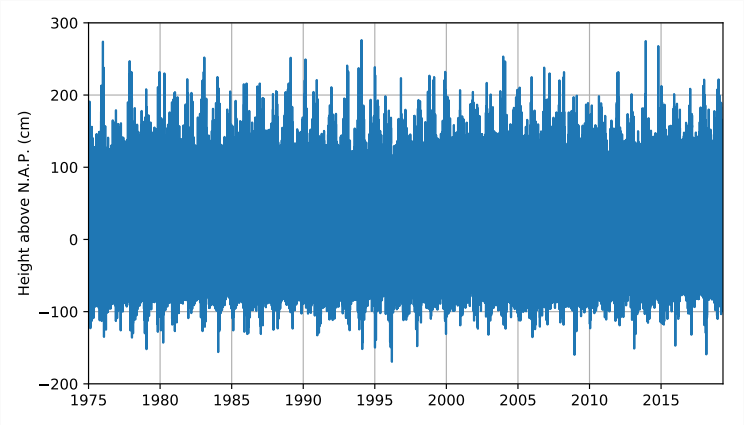
- Wind blows perpendicular to pressure gradient
- Isobars close to eachother: strong wind
- Due to this storm, water piles up at the coast

# How does that look in our tide-gauge record?




Data source: Rijkswaterstaat

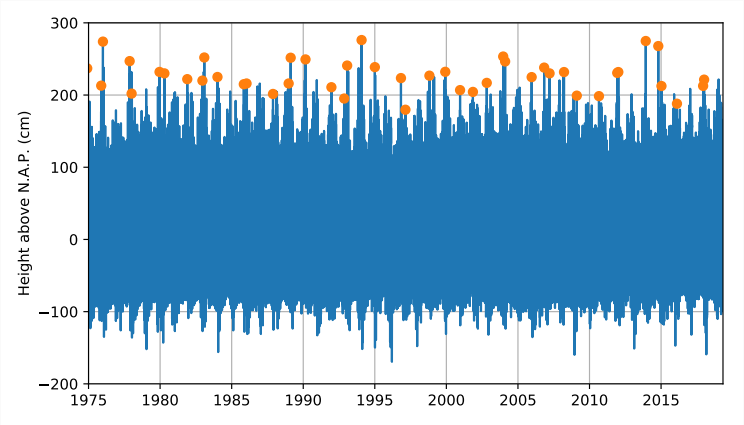
# Analysing storm surge characteristics




Source: Rijkswaterstaat

Can we estimate how often a specific surge will return? Yes, we can, using extreme-value statistics

# Analysing storm surge characteristics

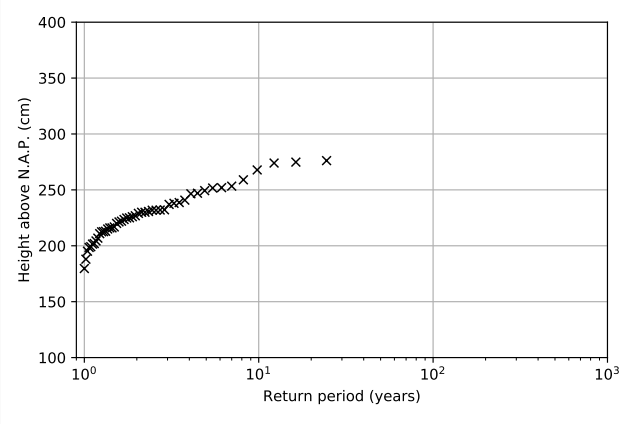



Source: Rijkswaterstaat

Can we estimate how often a specific surge will return? Yes, we can, using extreme-value statistics

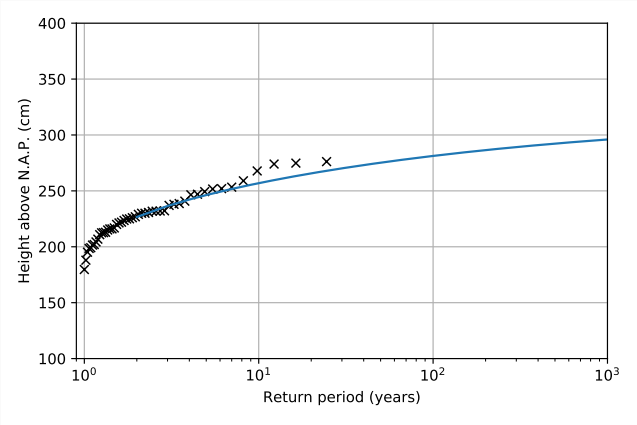
- First select extreme events
- In this case, each annual maximum

# Extreme-value analysis




We can estimate an extreme-value distribution from the maxima

# Extreme-value analysis



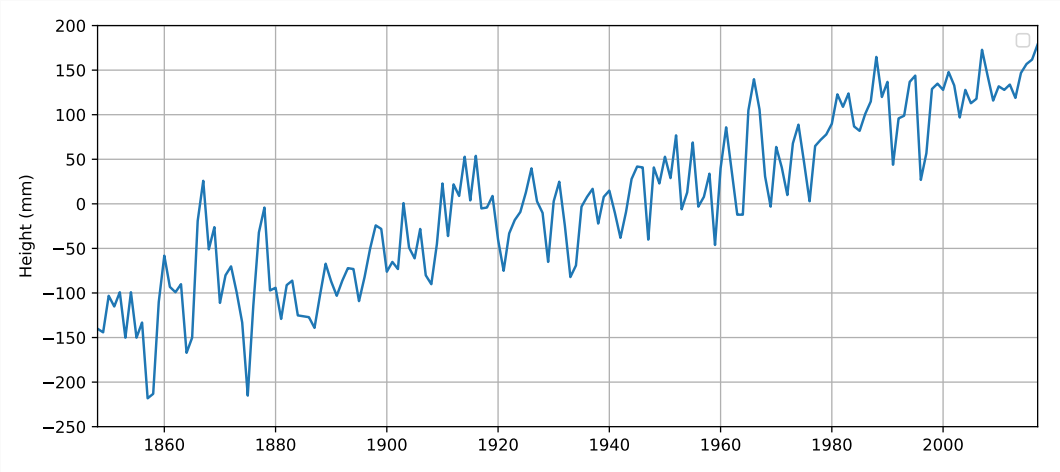

We can estimate an extreme-value distribution from the maxima

- Extreme-value return curve
- Expect a 1000-year event of $\sim$ 300 cm above NAP

# Long-term sea-level changes

# Long-term sea-level changes in Maassluis

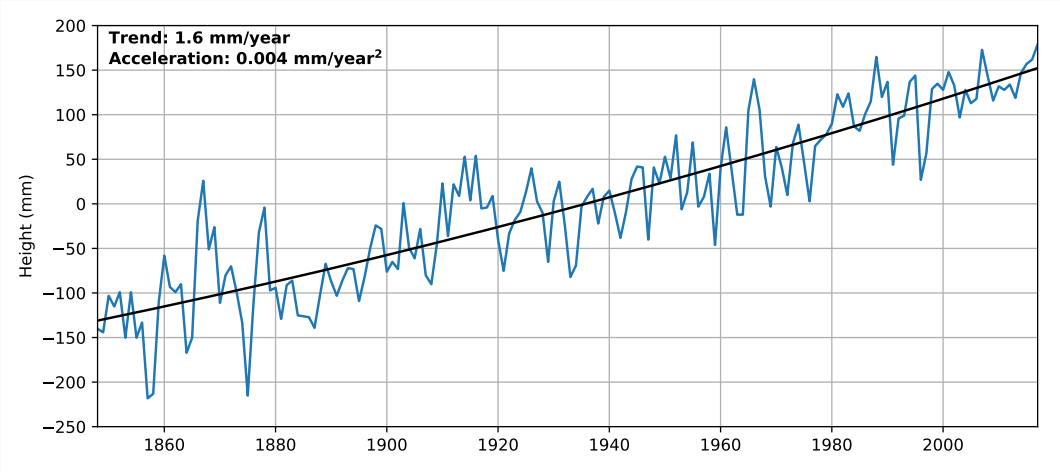
Continuous measurements since 1848




Source: PSMSL

# Long-term sea-level changes in Maassluis

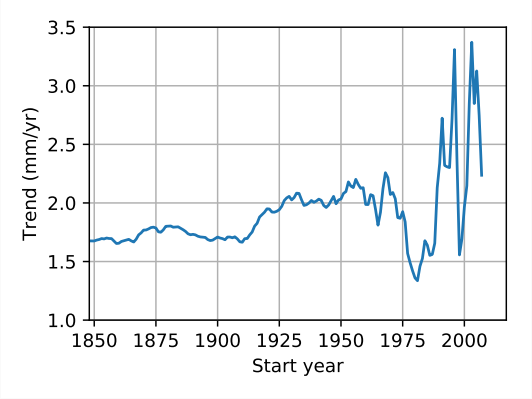
## Continuous measurements since 1848

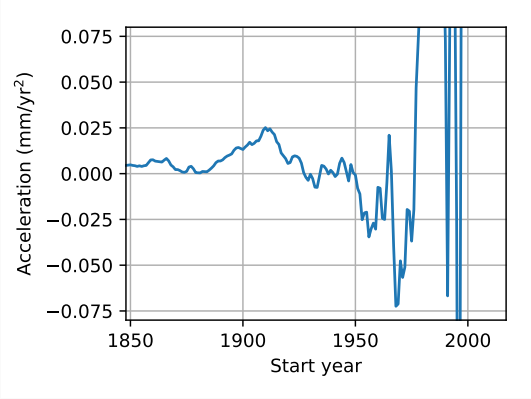



Source: PSMSL

# A caveat on trends and accelerations

Trends and accelerations are always computed over a specific period




Always ask about the start and end points when confronted with trends and accelerations!

# Estimating global-mean sea-level changes from tide-gauge records

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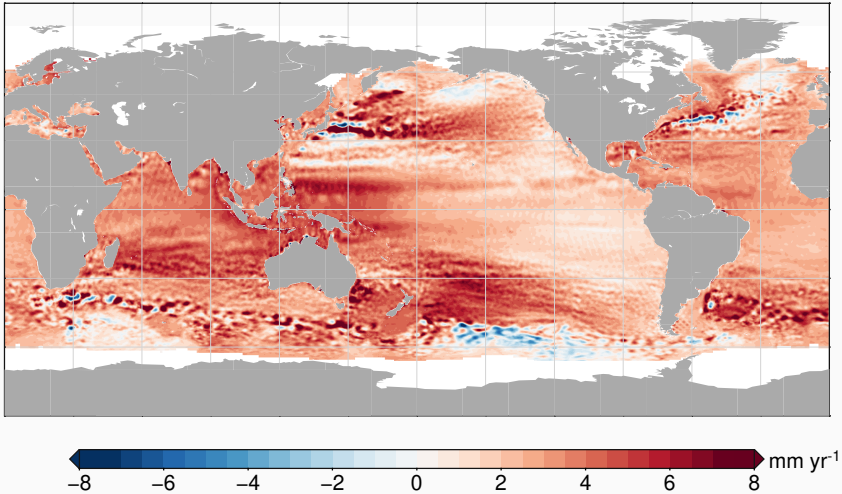
To answer this, we have to average the sparse tide-gauge observations.
This is challenging because:

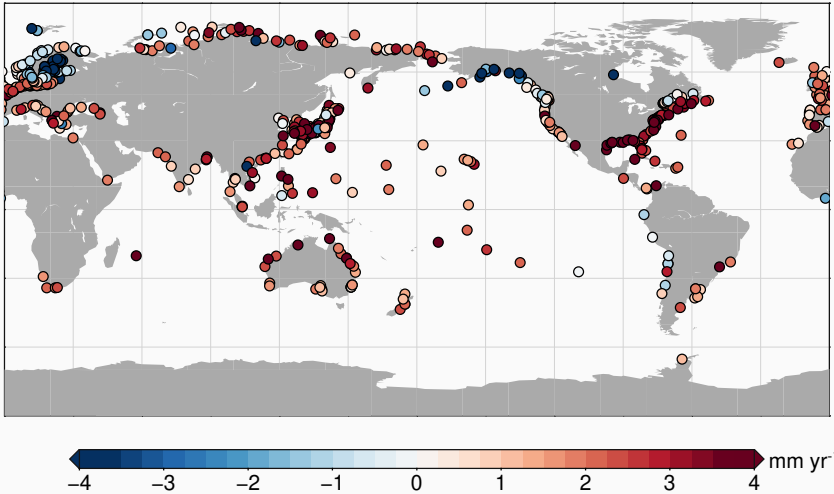
- Incomplete records with a lot of data gaps
- No even distribution over the oceans
- No single physical process causes a globally-uniform sea-level rise.

# Spatial variability in sea-level trends




Source: NASA MEaSUREs, PSMSL

# Spatial variability in sea-level trends

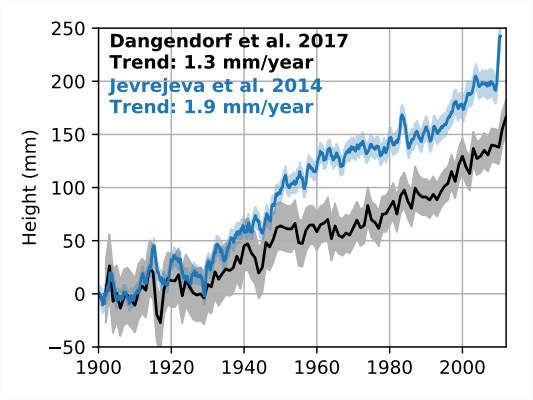



Source: NASA MEaSUREs, PSMSL

# Virtual station method

Straightforward way to average multiple records:

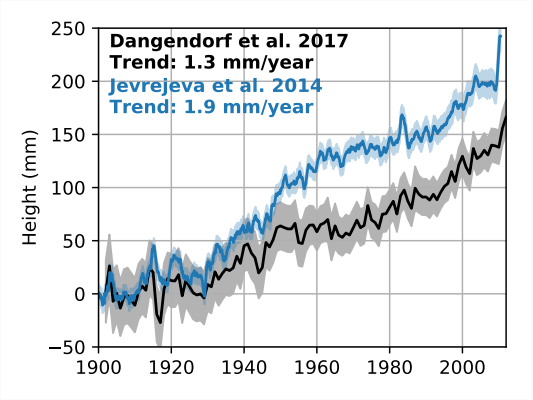
- Separate the global ocean into coherent regions
- Average two stations closest to each other into new 'virtual station' halfway
- Repeat until you only have a single station
- Last station is your regional curve
- Average regions to get global curve



# Virtual station method

Method is straightforward and easy to implement. However:

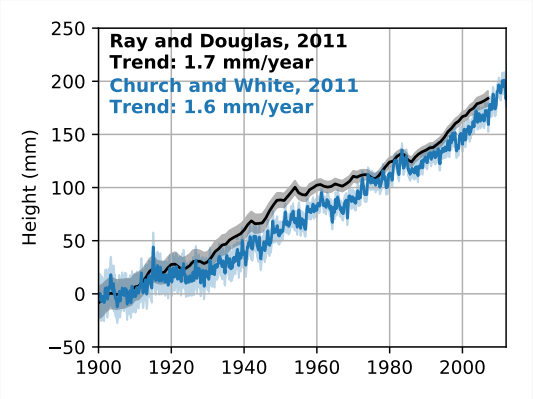
- Remote stations sometimes get very large weight
- Averaging stations is not trivial because they do not have common datum
- Difference in averaging causes largest difference between J14 and D17



# Empirical Orthogonal Functions

Use spatial patterns from satellite altimetry to estimate tide-gauge weight

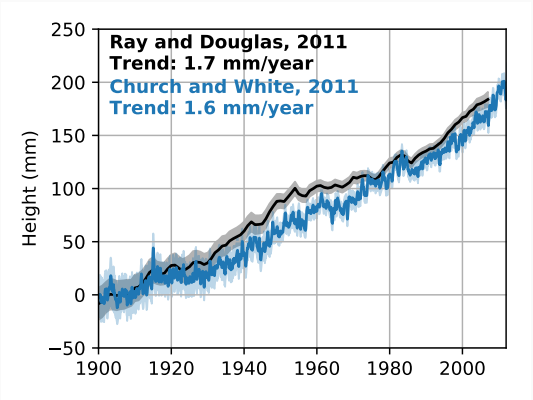
- Compute spatially coherent patterns in altimetry (EOFs)
- Estimate which tide gauges are representative for each pattern
- Extrapolate patterns back in time using these tide gauges
- This gives a spatio-temporal reconstruction, including GMSL



# Empirical Orthogonal Functions

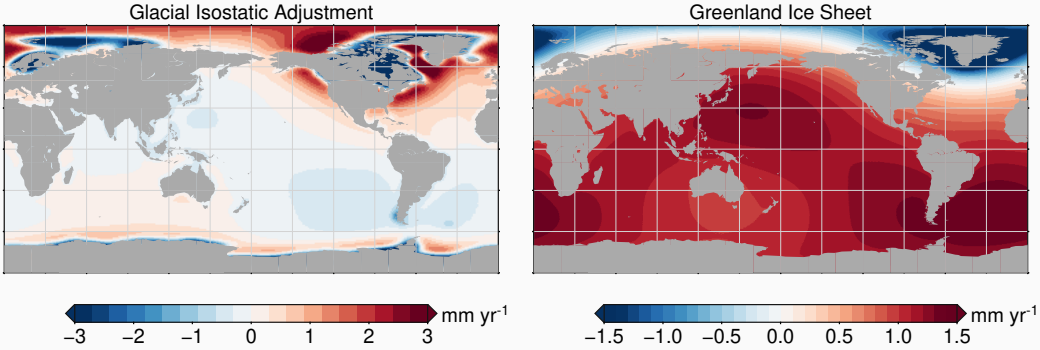
Much more realistic weighting of stations, but:

- Are altimetry patterns representative for whole century?
- Altimetry does not work well along coasts, where tide gauges are located
- There are problems when estimating the global mean curve from the EOFs (See Calafat et al. 2013).



# Towards including prior knowledge to the system

We know that many physical processes have distinct spatial fingerprints



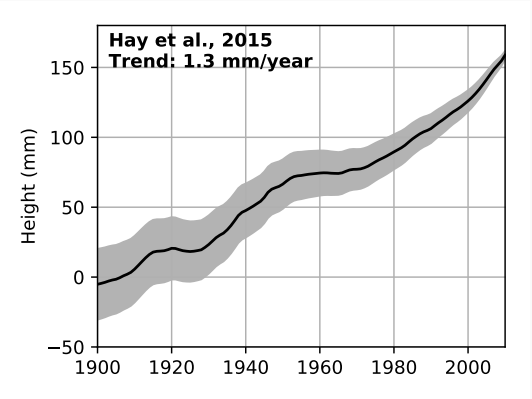

Source: GIA: Caron et al., 2018

Can we include them into the reconstructions?

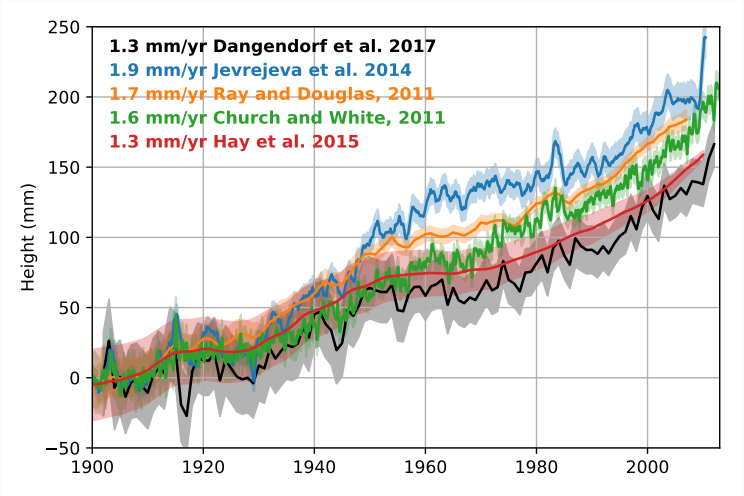
# Towards including prior knowledge to the system: Hay et al. 2015

An alternative approach by Hay et al., 2015: estimate the individual contributors to sea-level rise (ice/expansion etc) directly from tide-gauge data

- Determine spatial patterns of these contributors
- Build a statistical framework to estimate the contributors

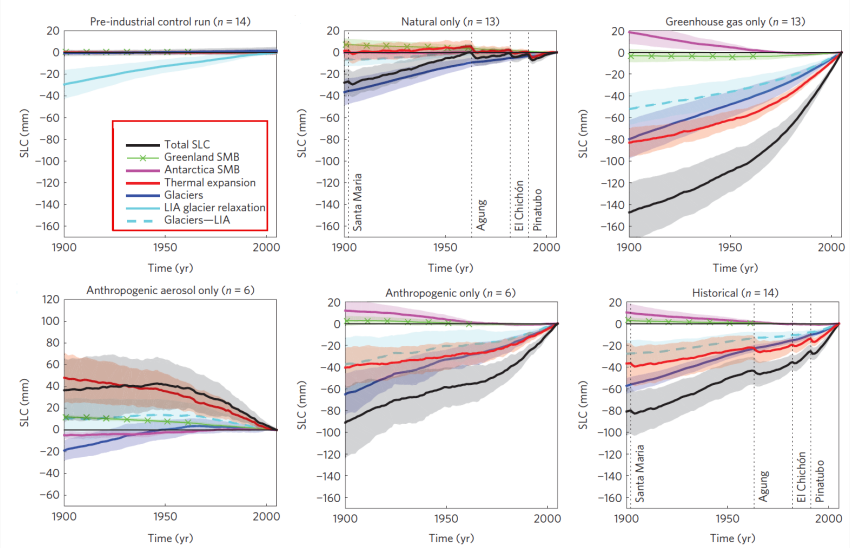


# Global reconstructions are not in agreement with each other




- Trends and variability differ between reconstructions.
- Reconstructions all show multi-decadal variability
- All agree with altimetry era
- All have positive acceleration

# Do we see a climate-change signal in sea-level records?




Source: Slangen et al., 2017, NGeo

# Summary

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- Measure and predict tides
- Measure storm surges and predict return periods
- Estimate long-term sea-level changes
- Reconstruct global sea level
- And there's much more!

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Keep a few things in mind:

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- Know what a tide gauge does and does not measure
- Isolate the signal you want to know
- Keep an eye on datums and benchmarks
- Tide gauges measure relative sea level